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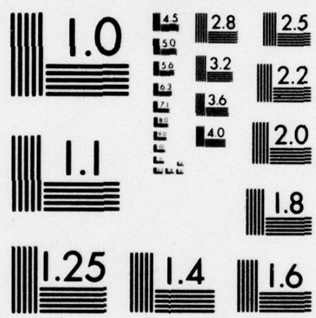

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VIBRATIONAL RESPONSE SPECTROSCOPY

Extension of Acoustic Emission Techniques to Combustion Diagnostic Use

by

John L. Eisel

Research Department

April 1977

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15. OUTLINE, TABLE OF CONTENTS, SUMMARY, OR EQUIVALENT DESCRIPTION

Vibrational response spectroscopy (VRS) is an attempt to adapt a relatively new technology to the study of the transition from deflagration to detonation (DDT) of high energy solid propellants.

This technology is actually two technologies very similar in concept but differing greatly in their range and area of application. They are vibrational analysis (the response of mechanical devices and structures to imposed mechanical vibrations), and acoustic emission (AE) analysis (the recording and assessing of stress waves in solid structures). Vibrational analysis usually operates in the frequency range from DC to 10-30 kHz. In contrast AE is concerned with frequencies from hundreds of kilohertz to several megahertz. VRS was initially intended to span the range from 0-200 kHz, but a number of preliminary findings have led to a planned extension to higher frequencies.

Although VRS depends on two fairly young technologies, there is a rather large body of experience reported in the literature in both AE and vibrational analysis. On the other hand, the applicaion of these separate technologies to the assessment of solid propellant combustion has met with quite limited success at the three laboratories at which it has been attempted. The present approach, however, which makes use of the strengths of both technologies and which has developed additional techniques to minimize the inherent uncertainties, builds on the prior attempts at combustion diagnosis and makes such diagnosis a viable possibility. This report serves as a preliminary discussion of an on-going investigation.

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INTRODUCTION

The transition from normal combustion of solid propellants, through anomalous combustion, to detonation occurs within a very short time interval. The ability to make accurate measurements of these events is critical to understanding the processes involved. Measuring devices used to assess normal propellant combustion processes are, in many instances, inadequate for studying the convective combustion and the transition to detonation. For instance: the high speed, high magnification photography used extensively at the Naval Weapons Center (NWC) to observe conductive burning of solid propellants is not capable of following processes occurring within the solid. Nor is the available framing rate adequate to follow the fast transients that occur. Similarly, although pressure transducers can be made responsive enough to follow rapid transients, they sense bulk, gas-phase manifestations of processes that they cannot directly detect. On the other end of the spectrum are devices such as thermocouples which are both too local and yet too large and slow for many needs.

Because of the inadequacies mentioned above, there is a need for new types of sensing devices or the adaptation of instrumentation used in other technologies to the investigation of the anomalous combustion processes.

VIBRATIONAL RESPONSE SPECTROSCOPY

EXPECTATIONS AND ADVANTAGES

Vibrational response spectroscopy (VRS) is an attempt to adapt a relatively new technology to the study of the transition from deflagration to detonation (DDT) of high energy solid propellants.

This technology is actually two technologies very similar in concept but differing greatly in their range and area of application. They are vibrational analysis (the response of mechanical devices and structures to imposed mechanical vibrations), and acoustic emission (AE) analysis (the recording and assessing of stress waves in solid structures). Vibrational analysis usually operates in the frequency range from DC to 10-30 kHz. In contrast AE is concerned with frequencies from hundreds of kilohertz to several megahertz. VRS was initially intended to span the range from 0-200 kHz, but a number of preliminary findings have led to a planned extension to higher frequencies.

Vibrational analysis is largely a technique used in structural analysis in which the source of energy is usually mechanical in nature (or at least the mechanical response of the structure to a different source of energy such as flutter of a fin). The energy sensed by AE technology is that of stress waves released in a solid by phenomena such as stress failure, corrosion, or crack propagation. VRS is expected to observe the energy released in the combustion process itself as well as any failure or cracking processes. The energy observed in any of these modes is a total, frequency dependent response of the structures, transducers, and source itself to the input energy; hence, the name chosen "vibrational response spectroscopy." Although vibrational analysis uses the frequency domain (power, phase, coherence, or frequency response as a function of frequency) as well as the time domain (total or rms power amplitude or correlation as a function of time), AE analysis rarely makes use of the frequency domain.

Unlike the measurement approaches used in observing conductive burning listed earlier, VRS has the advantage of sensing rapid energy release from the entire process rather than only a small region and being able to assess, through frequency analysis, the details of the energy release.

It is the hope and expectation that through appropriate use of the energy signal measurement and analysis, VRS will provide the ability to identify the processes of conductive combustion and the mechanical and combustion processes of convective combustion, and thereby assess DDT.

ACOUSTIC EMISSION FOR COMBUSTION ASSESSMENT

WORK AT OTHER LABORATORIES

A limited number of other laboratories have attempted to make use of the AE signal of propellant combustion.[1-8] These are the Air Force Rocket Propulsion Laboratory (AFRPL), Princeton University, and Georgia Institute of Technology.

Air Force Rocket Propulsion Laboratory

Although AE sensing had been used with regard to the combustion noise of flames,[1] it appears that AFRPL was the first to use this technique to assess the combustion of solid propellants. Koury reports[3] the use of AE sensors to determine the burn time and "quality" of burn

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[1]W. C. Strahle. "Some Results in Combustion Generated Noise," *Journal of Sound & Vibration*, 23, 113-125, 1972.

[2]R. L. Geisler, et.al. "Acoustic Emission System for Solid Propellant Burn Rate Measurements," Patent number 3899919, August 1975.

[3]Air Force Rocket Propulsion Laboratory. *Solid Strand Burn Rate Technique for Predicting Full Scale Motor Performance*, by J. Koury. Edwards, Calif., AFRPL, October 1973. (AFRPL-TR-73-49, publication UNCLASSIFIED.)

[4]------. *Combustion Stability Characteristics of Solid Propellants*, by C. P. Wendelken. Edwards, Calif., AFRPL, October 1973. (AFRPL-TR-73-63, publication UNCLASSIFIED.)

[5]A. J. Saber, et.al. "Acoustic Emissions from Burning Propellant Strands," in *Proceedings of the Eleventh JANNAF Combustion Meeting, Pasadena, Calif., 9-13 September 1974*. (Chemical Propulsion Information Agency Publication No. 261, Vol. I, December 1974, publication UNCLASSIFIED.) (Cited hereafter as *Eleventh JANNAF Proceedings (Vol. I)*.)

[6]W. C. Strahle. "The Role of Combustion Noise in Solid Propellant Combustion Instability," in *Eleventh JANNAF Proceedings (Vol. I)*.

[7]Air Force Office of Scientific Research. *Audible and Ultrasonic Acoustic Emission from Composite Solid Propellants*, by J. I. Craig, et.al., Georgia Institute of Technology. Arlington, Va., AFOSR, July 1975. (AFOSR Interim Report, publication UNCLASSIFIED.)

[8]James I. Craig, et.al. "Study of Unsteady Combustion of Heterogeneous Solid Propellants by Analysis of Acoustic Emissions," abstract submitted to *15th AIAA Aerospace Sciences Meeting*, January 1977.

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of a strand. The AFRPL work consistently used only the rms value of the sensed energy--the time domain. An erratic rms envelope was determined to represent non-smooth combustion of the strand and could indicate side-burning, the presence of a void, or "sudden changes in burning." Such use of AE techniques is covered in a patent by Geisler, Koury, and Johnston.[2] The frequency range is from 100-300 kHz, and the use seems to be limited to the measurement of burning rates of propellants. The patent claims the source of the acoustic energy to be "created by thermal fracture or deflagration of a solid oxidizer in the propellant."

Further AFRPL use of the technique--still rms energy as a function of time--is reported by Wendelken.[4] Here, AE is mentioned as a means of detecting ignition and burnout in T-burner testing. Wendelken proposes the use of the AE signal as being possibly superior to the pressure-time record for ascertaining the time of burn of the samples. This technique is in general use at AFRPL for both strand burning rate and T-burner measurements,* but no further mention of it in the literature has been found.

Princeton University

The Air Force Office of Scientific Research (AFOSR) has funded AE work at both Princeton University and Georgia Institute of Technology.

The only report of the Princeton work[5] indicated that, like AFRPL, the frequency range used was 100-300 kHz. This choice of frequency was chosen based on "characteristic times of non-steady processes of flame zone reactions and heterogeneous gas structure." (Note the shift in source of emissions from the oxidizer crystal fracture or deflagration cited by AFRPL.) The Princeton group attempted to do spectral analysis of their signals, but from observation of their spectral distributions or power spectral densities (PSD), it is clear that their energy distribution was dominated by system and/or transducer resonances. They were able to observe changes in energy distribution as a function of ammonium perchlorate (AP) particle size, mean pressure, burn area, and burn medium (they burned both under water and in oil).

As AP particle size was increased the contributions at high frequency were seen to grow and the entire spectrum to "smooth out." No consistent trends were seen as a function of mean pressure. As the burning surface area was increased by a factor of four, peaks and valleys "only hinted at previously" were seen indicating that resolution might

*Personal communication with R. Geisler, AFRPL, December 1976.

depend on sufficient total energy release. Finally, when oil replaced water as the medium surrounding the burning strand there was "little comparison in the spectral features," implying possible chemical reaction between products of combustion and the surrounding medium. Although no identification of sources of spectrally isolated contributions were possible, the Princeton group expressed encouragement with respect to the technique.

Georgia Institute of Technology

Perhaps the most extensive investigation of AE from burning solid propellants has been done at the Georgia Institute of Technology. Initially Strahle reported[6] use of combustion generated noise from 0-13 kHz (the audible range obtained by use of a microphone pickup). This is in the same frequency range as the vibrational analysis technique, but the mode of energy pickup and the source of the energy are sufficiently different to warrant calling this a new technique. Spectral analysis was performed showing rather broad band noise with most of the sound power below 2000 Hz. There was a "pronounced peak" at 600-700 Hz. The work was continued by Craig.[7] Craig acknowledges that neither flat response transducers nor satisfactory calibration techniques exist in the ultrahigh frequency acoustic emission (UHFAE) region—50-300 kHz. (The upper frequency limit of their tape recorder was 300 kHz). Craig gives three reasons for lack of adequate understanding of spectral features of UHFAE.

1. The emission originates in finite, bounded materials so that the emission signal is combined with the system response.

2. No adequate transducers exist.

3. The stress waves to be measured are attenuated by the medium through which they pass.

He states that as normally used by structures people in observing the amplitude or energy per emission during transients, measurements are possible, and have meaning; but those of continuous acoustic signals are less clear. In terms of spectral analysis, neither transient nor continuous signals yield straightforward results. The problem is due to the inability to account for transducer resonances.

The Georgia Institute of Technology reports use of "number of crossings" technique and found it of "little use." They also tried the

rms signal level approach by which they recognized ignition and burnout, but did not understand the rise in level during burning. The report includes examples of PSDs as a function of time during a single test, comparison of PSDs from test to test as a function of AP particle size, comparison of PSDs of the same propellant burned in air and in nitrogen, and comparison of PSDs of propellants containing aluminum with and without AFCAM coating.

A report of the latest Georgia Institute of Technology work was presented at the 15th AIAA Aerospace Sciences Meeting.[8] In this latest work they attempt to correct the PSD for errors due to transducer and system resonances. This is done by subtracting off the transducer response as "determined" by electrical stimulation and by making the transmission path to the transducer as short and clean as possible. Their findings were as follows: for nonaluminized propellants, no effect of AP particle size could be seen. When air was substituted for nitrogen as the pressurizing gas, a shift in spectral peaks and peak power was seen along with a general smoothing of the spectrum below 125 kHz. Inclusion of aluminum in the propellant leads to a "markedly different" spectrum below 225 kHz with high noise below 125 kHz and more distinctive peaks between 125 and 225 kHz. There seemed to be mixed results with regard to an AFCAM coating on the added aluminum. Addition of a catalyst led to an overall increase in power of about 10 dB and higher relative noise from 200 to 300 kHz. In addition to spectral data reduction, rms energy levels were also extracted and correlations between high and irregular burning rates with high AE levels were noted.

WORK AT THE NAVAL WEAPONS CENTER

The work performed thus far at NWC is not a new technique even though a different name (vibrational response spectroscopy) is applied to it. The name change simply recognizes and emphasizes that the vibrational or acoustic energy measured is influenced by the response of the total system: sample, transducer, and structure. From the beginning the work at AFRPL, Princeton, and Georgia Institute of Technology has been cited as the basis which engendered the NWC work.[9] With the exception of the Georgia Institute of Technology, it appears that other

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[9] R. L. Derr. "Combustion of High Energy Propellants: Relation to Deflagration to Detonation," presented at *HEPS Program Review*, China Lake, Calif., 9 December 1975.

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SUMMARY

Although VRS depends on two fairly young technologies, there is a rather large body of experience reported in the literature in both AE and vibrational analysis. On the other hand, the application of these separate technologies to the assessment of solid propellant combustion has met with quite limited success at the three laboratories at which it has been attempted. The present approach, however, which makes use of the strengths of both technologies and which has developed additional techniques to minimize the inherent uncertainties, builds on the prior attempts at combustion diagnosis and makes such diagnosis a viable possibility. This report serves as a preliminary discussion of an on-going investigation.

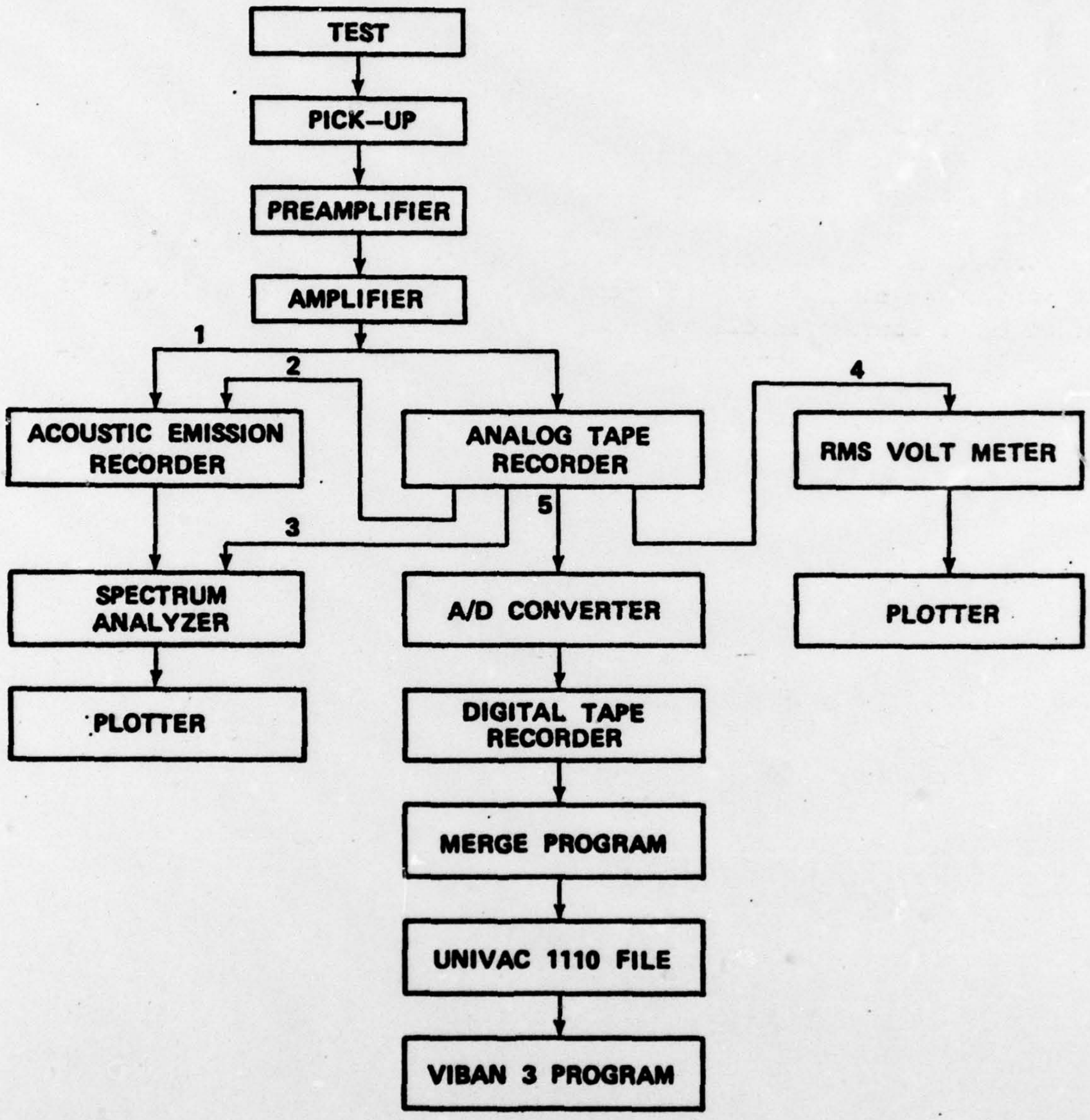

FIGURE 1. Data Handling Schemes for Acoustic Emission Data.

laboratories have not directed attention at the fundamental barrier to productive use of the AE approach to combustion diagnostics, viz., the interaction of sample, transducer, and structure with the energy released by the combustion processes prior to output of the transduced signal. (The work as reported by the Georgia Institute of Technology appears to be on the right track.)[8]

The use of the rms energy level as an indicator of anomolous combustion was pioneered by AFRPL. Recently this concept was used in the flashdown experiments of J. L. Prentice.[10] The use of that technique, rather than being an end in itself, was a stop-gap to allow the flashdown work to proceed while a more sophisticated sensing and analysis system was developed.

Toward this end preliminary tests were conducted to demonstrate that burning propellants do yield unique and reproducible AE signals.[10] In these tests it was clear that propellant type as well as transition to anomolous (flashdown) combustion led to unique spectra. It was further shown that transducer mounting was a critical parameter. These tests were only preliminary and indicated that: (1) more work was worthwhile since the information desired was present albeit greatly masked, and (2) the effects of transducer and structure resonances were the dominant features and needed to be removed from subsequent signals before the technique could meet its potential.

Acoustic emission data at NWC can be handled in five ways. These five methods are combinations of three separate sets of instrumentation. Figure 1 indicates that all the schemes begin in the same manner; with the sensing of the test signal by a transducer and amplification of the signal to a level sufficient to input to the subsequent devices. The outputs of five schemes are listed in Table 1. The transducer is either an accelerometer or an AE transducer depending on the frequency to be observed.

In scheme 1 the amplified signal is recorded directly by an AE recorder (Acoustic Emission Technology). This modified video recorder allows the 16 ms of test to be stopped and then to be gated further to as low as 2 μs. This signal is continuously scanned in the video system and the output is fed to a spectrum analyzer (Saicor 52C) which calculates the PSD of the signal for plotting.

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[10]Naval Weapons Center. *Research Conducted at the Naval Weapons Center in Support of High Energy Propellant Safety (HEPS) Program, Technical Progress Report, 1 March through 31 May 1976*, by Aerothermochemistry and Advanced Technology Divisions. China Lake, Calif., NWC, June 1976. (Publication UNCLASSIFIED.)

Scheme 2 is the same as scheme 1 except that the amplified signal is recorded on analog tape and then time expanded to an appropriate degree prior to recording on the AE recorder. Schemes 1 and 2, by using the gated stop-action of the AE recorder, provide a means for resolving transient behavior the time duration of which is too short for the relatively slow Saicor spectrum analyzer to handle directly.

The most direct, quick-look scheme is number 3. In this sequence the analog-recorded and time-expanded signal is fed directly into the spectrum analyzer for a PSD analysis of steady, or average data.

Scheme 4 is essentially that pioneered by AFRPL. The analog-recorded and time-expanded signal is fed into an rms volt meter whose analog output is directly plotted. The result is a time history of the acoustic energy level. This technique is useful for determining the length of the test, the "evenness" of the test, and the time and degree of any anomalous behavior.

The most complex scheme, but the one which yields the most detailed analysis, is scheme 5. This sequence makes use of a very complex fast fourier transform program developed by NASA. The program is called VIBAN 3 and is run on the UNIVAC 1110 computer.[11] The outputs of VIBAN 3 are listed in Table 1. The means by which maximum information may be extracted from these multiple outputs of VIBAN 3 are discussed in some detail by Parmenter and Christiansen.[12]

The A/D converter and digital tape unit create a single file consisting of a header listing the identification number, file number, and sampling time; and 2731 "words", generated by combining three 10-bit (0-1023 octal) digital readouts/"word".

The VIBAN 3 program expects one or more channels of scaled data plus a shared time base, written in 2000 word blocks in alternating fashion, i.e., TIME, CHAN1, CHAN2, ... CHANN; TIME, CHAN1, CHAN2, etc.

It is the purpose of program MERGE to create a tape compatible with VIBAN 3 input from up to four separate files created by the A/D converter. The files to be merged to not need to be continuous, and forward/backward skipping on the A/D output tape is possible. Individual calibration constants (units/A/D count) are input for each channel and are utilized in scaling the digital sample to engineering units; the time base is generated from the sample rate.

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[11] Naval Weapons Center. *Users Manual for NWC Spectral Analysis Computer Program*, by R. G. Christiansen and R. F. Klever. China Lake, Calif., NWC, November 1972. (NWC TP 5372, publication UNCLASSIFIED.)

[12] W. W. Parmenter and R. G. Christiansen. "Recovery of Modal Information from a Beam Undergoing Random Vibration," in *Transaction of ASME Journal of Engineering for Industry*. Paper No. 73-WA/DE-10, ASME, November 1974, pp. 1307-1313.

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TABLE 1. Outputs of Data Reduction Schemes.

Scheme	Output	Use
1	Power spectral density	Acoustic power as function of frequency
2	Power spectral density	Acoustic power as function of frequency
3	Power spectral density	Acoustic power as function of frequency
4	rms energy-time	Integrated acoustic energy as function of time
5	Probability density	Signal content-random/periodic
	Auto correlation	Detection of periodicus in noise spectrum
	rms acceleration	Vibration level as function of frequency
	Power spectral density	Acoustic power as function of frequency
	Cross correlation	Dependence of one signal on another
	Cross spectrum	Estimates of input signal from output measurement
	Coincidence spectrum	In-phase component of cross spectrum
	Quadrature spectrum	Out-of-phase component of cross spectrum
	Phase spectrum	Zero crossings at resonant frequencies
	Coherence	Degree to which two signals are identical in frequency
	Frequency response function	Response of system to input energy

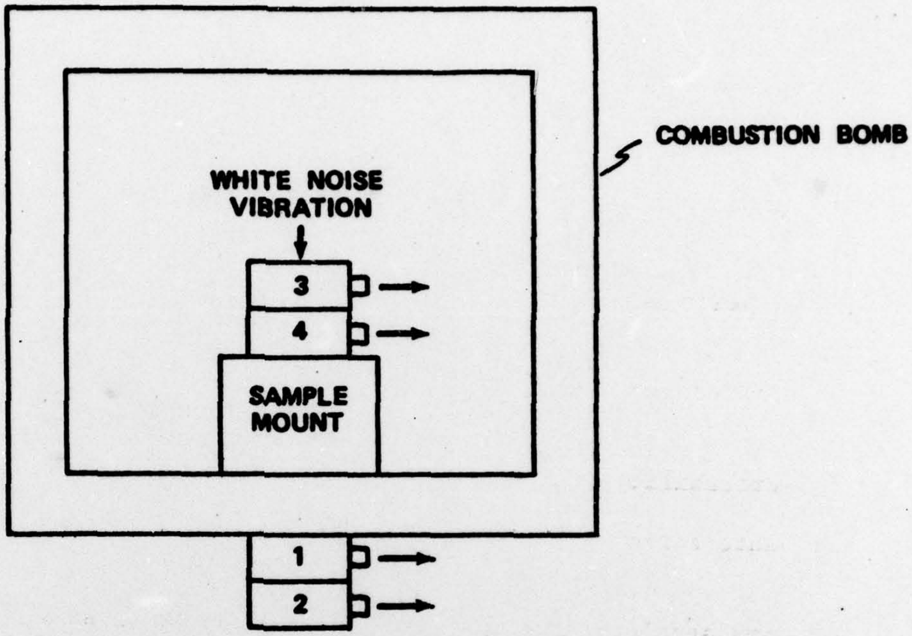

FIGURE 2. Schematic Drawing of Experimental Set-up With Four Acceleration Sensitive Transducers for System Transform Determination.

9. Calculate output PSD of subsequent tests unbiased by transducer and system (mechanical) resonances using the same transducer (transducer 1, mounted as before) and then calculate the unbiased input signal due to combustion: $G = G_1/|H_{1,3}|^2$.

Such a scheme should provide a greatly enhanced capability for observing the energy spectrum of the combustion processes of interest. The calculations outlined above are well within the capabilities of the VIBAN 3 program and programs to merge multiple inputs and to store the transfer function have been prepared. This capability, along with the schemes described earlier to capture the rapid transients of the transitions from normal to abnormal combustion, should provide the diagnostic means necessary to observe the details of solid propellant combustion during the transitions.

The understanding of the combustion energy spectra, once they become available, is a wholly separate issue and will have to be resolved systematically at that time.

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The only restriction of the program is that the sections of the digitized tape to be merged must have been sampled at the same rate; no provision has been provided for sample rate adjustment.

The program has been checked out with synthetically generated data (audio oscillator signal) and the merged tape was successfully processed by VIBAN 3.

In order to circumvent the problems associated with total system response previously discussed, a procedure has been devised to obtain the overall frequency response function of the entire system from propellant sample through the transducer. Such a function will provide the ability to form the product of a PSD obtained in the usual manner by a frequency response function for the entire system and thereby get directly the power spectrum of the combustion process alone. The sequence to accomplish this is outlined below (refer to Figure 2 to identify positions 1, 2, 3, and 4).

1. Set up entire system to be used in combustion experiments as per Figure 2, using four transducers. Transducers 1 and 2 form a pair of dissimilar transducers with regard to their resonances, as do 3 and 4.

2. Input a white noise, broad band vibration into transducer 3.

3. Calculate the input PSDs, G_3 and G_4 from the outputs of transducers 3 and 4.

4. Calculate frequency response function between 3 and 4, $H_{3,4}$.

5. Then calculate a corrected input PSD, G'_3, from $G'_3 = G_{3,4}/H_{3,4}$. This PSD should be unbiased by input transducer resonance.

6. Similarly, calculate a corrected output PSD, G'_1, from the output PSDs G_1 and G_2 along with their frequency response function, $H_{1,2}$.

7. Calculate the cross PSD between G'_3 and G'_1, $G'_{1,3}$.

8. Calculate the system frequency response function, $H_{1,3}$, from $H_{1,3} = G'_{1,3}/G'_1$. This frequency response function is a constant for the system as long as the system is not altered. (Determination of the effect of removing transducers 2, 3, and 4 will have to be made.)